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ON COALITION FORMATION: A GAME-
THEORETICAL APPROACH

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ON COALITION FORMATION: A GAME-THEORETICAL APPROACH

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ABSTRACT

This paper deals with the question of coalition formation in n-person cooperative games. Two abstract game models of coalition formation are proposed. We then study the core and the dynamic solution of these abstract games. These models assume that there is a rule governing the allocation of payoffs to each player in each coalition structure called a payoff solution concept. The predictions of these models are characterized for the special case of games with side payments using various payoff solution concepts such as the individually rational payoffs, the core, the Shapley value and the bargaining set $M_1^{(i)}$. Some modifications of these models are also discussed.

AMS (MOS) Subject Classifications: 90D12, 90D45

Key Words: coalition formation, abstract games, core, dynamic solution, individually rational payoffs, Shapley value, bargaining set

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SIGNIFICANCE AND EXPLANATION

The theory of n-person cooperative games is a mathematical theory of coalition behavior. A fundamental problem posed in game theory is to determine what outcomes are likely to occur if a game is played by "rational players". I.e. given an n-person cooperative game, it is natural to inquire (1) what will be the final allocation of payoffs to each of the players and (2) which of the possible coalitions can be expected to form.

Since the publication in 1944 of the monumental work Theory of Games and Economic Behavior [15] by von Neumann and Morgenstern, most of the research in n-person game theory has been concerned explicitly with predicting players' payoff and only implicitly (if at all) with predicting which coalitions shall form. In this paper, the primary emphasis is on the second aspect of coalition behavior, namely the formation of coalitions.

Two models of coalition formation are proposed based on the theory of n-person games. As in most of game theory, our models are normative and use only endogenous arguments, that is, only information contained in the characteristic function is used.

The responsibility for the wording and views expressed in this descriptive summary lies with MRC, and not with the author of this report.

ON COALITION FORMATION: A GAME-THEORETICAL APPROACH

Prakash P. Shenoy

1. Introduction

The theory of n-person cooperative games is a mathematical theory of coalition behavior. A fundamental problem posed in game theory is to determine what outcomes are likely to occur if a game is played by "rational players". I.e. given an n-person cooperative game, it is natural to inquire (1) what will be the final allocation of payoffs to each of the players and (2) which of the possible coalitions can be expected to form. These two aspects of coalition behavior are closely related. The final allocation of payoffs to each of the players depend on the coalitions that finally form, and the coalitions that finally form depend on the available payoffs to each player in each of these coalitions. Since the publication in 1944 of the monumental work Theory of Games and Economic Behavior [15] by von Neumann and Morgenstern, most of the research in n-person game theory has been concerned explicitly with predicting players' payoff and only implicitly (if at all) with predicting which coalitions shall form. In this paper, the primary emphasis is on the second aspect of coalition behavior, namely the formation of coalitions. Two models of coalition formation are proposed based on the theory of n-person games. As in most of game theory, our models are normative and use only endogenous arguments, that is, only information contained in the characteristic function is used.

A brief review of abstract games and its solutions is presented in Section 2. In Section 3, two abstract game models of coalition formation are proposed. In one approach, payoff allocations and coalition structures are modeled as the outcomes of an abstract game on which an appropriate domination relation is

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defined. In another approach, coalition structures alone are modeled as outcomes. In both cases, we study the core and the dynamic solution of the abstract game. The two models are then compared. Section 4 deals with the representation of the models by means of digraphs. In Sections 5-8, the solutions of the abstract games are characterized for the special case of games with side payments using various payoff solution concepts such as the individually rational payoffs, the core, the Shapley value and the bargaining set $M_1^{(i)}$. Finally in Section 9, we discuss possible modifications in the definition of the domination relation in the case where coalition structures alone are modeled as outcomes.

2. Abstract Games and their Solutions

An abstract game is a pair (X, dom) where X is an arbitrary set whose members are called outcomes of the game, and dom is an arbitrary binary relation defined on X and is called domination. An outcome $x \in X$ is said to be accessible from an outcome $y \in X$, denoted by $x \leftarrow y$ (or $y \rightarrow x$), if there exists outcomes $z_0 = x, z_1, \dots, z_{m-1}, z_m = y$, where m is a positive integer such that

$$(2.1) \quad x = z_0 \text{ dom } z_1 \text{ dom } z_2 \text{ dom } \dots \text{ dom } z_{m-1} \text{ dom } z_m = y.$$

Also assume $x \leftarrow x$, i.e. an outcome is accessible from itself. Clearly the binary relation accessible is reflexive and transitive. Two outcomes x and y which are accessible to each other are said to communicate and we write this as $x \leftrightarrow y$. Since the relation accessible is transitive and reflexive, it follows that

Proposition 2.1. Communication is an equivalence relation.

We can now partition the set X into equivalence classes. Two outcomes are in the same equivalence class if they communicate with each other.

The set

$$(2.2) \quad \text{Dom}(x) = \{y \in X : x \text{ dom } y\}$$

is called the dominion of x . Also, we define the dominion of any subset $A \subset X$ by

$$(2.3) \quad \text{Dom}(A) = \bigcup_{x \in A} \text{Dom}(x) .$$

The core C (due to Gillies [9] and Shapley) of an abstract game is defined to be the set of undominated outcomes. I.e.

$$(2.4) \quad C = X - \text{Dom}(X) .$$

We can rewrite the definition of the core in terms of the relation accessible as follows.

$$(2.5) \quad C = \{x \in X : \forall y \in X, y \neq x, \text{ we have } y \not\leftarrow x\} .$$

I.e., in the terminology of Markov chains, the core is the set of all absorbing outcomes. Note that each outcome in the core (if nonempty) is an equivalence class by itself.

An elementary dynamic solution (elem. d-solution) of an abstract game is a set $S \subset X$ such that

$$(2.6) \quad \text{if } x \in S, y \in X - S \text{ then } y \not\leftarrow x, \text{ and}$$

$$(2.7) \quad \text{if } x, y \in S, \text{ then } x \leftarrow y \text{ and } y \leftarrow x .$$

It can easily be shown that

Proposition 2.2. An elem. d-solution is an equivalence class.

The converse, however, is not always true. Condition (2.6) require S to be (in the terminology of Markov chains) a non-transient (recurrent, persistent) equivalence class.

The dynamic solution (d-solution) P of an abstract game is the union of all distinct elem. d-solutions. I.e.

$$(2.8) \quad P = \bigcup \{S \subset X : S \text{ is an elem. d-solution}\} .$$

We have the following easy result.

Proposition 2.3. For all abstract games, $C \subset P$.

It is clear that the dynamic solution always exists and is unique. However, it may sometimes be empty. However, if X is a finite set, we have the following two results.

Lemma 2.4. If X is a finite set, then P is the d-solution if and only if P satisfies

$$(2.9) \quad \forall x, y \in P, y \prec x \text{ iff } x \prec y.$$

$$(2.10) \quad \text{If } x \in P, y \in X - P, \text{ then } y \not\prec x. \text{ And}$$

$$(2.11) \quad \text{If } y \in X - P, \text{ then } \exists x \in P \text{ such that } x \prec y.$$

Theorem 2.5. If X is a finite set, then the d-solution is always nonempty.

For proofs of these assertions and for a behavioral interpretation of the dynamic solution, see Shenoy [21]. The dynamic solution has also been defined independently by Kalai, Pazner and Schmeidler [11,12].

3. The Models

We shall first introduce some notation and definitions. Let $N = \{1, \dots, n\}$ denote the set of players. Let Γ be an n-person cooperative game (with side payments, without side payments or a game in partition function form). Let 2^N denote the set of all subsets (coalitions) of N and Π denote the set of all partitions (coalition structures) of N . Let $S : \Pi \rightarrow 2^{E^n}$ be a payoff solution concept, where 2^{E^n} denotes the set of all subsets of the n-dimensional Euclidean space E^n . Intuitively, given that the players in N align themselves into coalitions in the c.s. $P \in \Pi$, we interpret $S(P)$ as the set of all likely disbursements of payoffs to players in N . E.g. S may denote the individually rational payoffs, the core, a vN-M stable set, the Shapley value, the bargaining set $M_1^{(i)}$, the kernel, the nucleolus or any

other payoff solution concept that indicates disbursement of payoffs as solutions of an n-person cooperative game. For $P \in \Pi$, $S(P)$ may be the empty set \emptyset (e.g. the core), or a single point in E^n (e.g. the Shapley value or the nucleolus) or a nonempty subset of E^n (e.g. the bargaining set $M_1^{(i)}$ or the kernel). If $S(P) = \emptyset$ (interpreting this fact as players unable to reach an agreement on the disbursement of payoffs when they are aligned into coalitions in P), then we will assume for simplicity of exposition that P is not viable. Let $\Pi(S)$ denote the set of all viable coalition structures with respect to the payoff solution concept (p.s.c.) S , i.e.,

$$(3.1) \quad \Pi(S) = \{P \in \Pi: S(P) \neq \emptyset\}.$$

Definition 3.1. A solution configuration with respect to p.s.c. S is a pair (x, P) such that $x \in S(P)$ and $P \in \Pi(S)$.

A solution configuration w.r.t. p.s.c. S represents a possible outcome of the n-person cooperative game where S represents any appropriate payoff solution concept. Let $SC(S)$ denote the set of all solution configurations w.r.t. p.s.c. S , i.e.

$$(3.2) \quad SC(S) = \bigcup_{P \in \Pi(S)} [S(P) \times \{P\}]$$

We now define a binary relation, domination, on the set $SC(S)$ as follows:

Definition 3.2. Let (x, P_1) and (y, P_2) belong to $SC(S)$. Then (x, P_1) dominates (y, P_2) , denoted by $(x, P_1) \text{ dom } (y, P_2)$ iff

$$(3.3) \quad \exists \text{ a nonempty } R \in P_1 \text{ such that } x_i > y_i \text{ for all } i \in R.$$

Intuitively, if $(x, P_1) \text{ dom } (y, P_2)$, then the players in some coalition R in c.s. P_1 prefer P_1 to P_2 . We require the players in subset R to be together in a coalition in c.s. P_1 so that there is no conflict of interest between these player's preference for P_1 and their allegiance to the other players in their coalition.

The dominance relation as defined above may be neither asymmetric nor transitive. We now have an abstract game $(SC(S), \text{dom})$ where $SC(S)$ is the set of outcomes and dom is a binary relation on $SC(S)$. For this abstract game, we look at the core and the dynamic solution as defined in Section 2.

Definition 3.3. Let Γ be an n-person cooperative game[†] and S be a p.s.c. The core of solution configurations w.r.t. p.s.c. S , denoted by $J_0(S)$, is the core of the abstract game $(SC(S), \text{dom})$.

Definition 3.4. Let Γ be an n-person cooperative game and S be a p.s.c. The dynamic solution of solution configurations w.r.t. p.s.c. S , denoted by $J_1(S)$, is the dynamic solution of the abstract game $(SC(S), \text{dom})$.

From Proposition 2.3, we obtain the following result.

Proposition 3.1. $J_0(S) \subset J_1(S)$.

The core of an abstract game is a very intuitive and plausible solution concept. However, for some games and for certain p.s.c., $J_0(S)$ may be an empty set. In such cases, we can proceed to look at $J_1(S)$ as a solution concept. If the p.s.c. S is such that $S(P)$ is a unique

[†]In this section, Γ denotes an n-person cooperative game with side payments, without side payments or a game in partition function form.

point in E^n for each $P \in \Pi(S)$ with $\Pi(S) \neq \emptyset$, then the set $SC(S)$ is finite and nonempty. By appealing to Theorem 2.5, we conclude the following result.

Proposition 3.2. Let Γ be an n -person cooperative game and S be a p.s.c. such that $\Pi(S) \neq \emptyset$ and assume that $S(P)$ is a unique point in E^n for each $P \in \Pi(S)$. Then $J_1(S) \neq \emptyset$.

In another approach, we model just the set of all viable coalition structures $\Pi(S)$ as the outcomes of an abstract game. A domination relation on $\Pi(S)$ is defined as follows.

Definition 3.5. Let $P_1, P_2 \in \Pi(S)$, $\emptyset \neq R \in 2^N$ and S be a p.s.c. Then P_1 dominates P_2 via R w.r.t. p.s.c. S , denoted by $P_1 \text{ dom}_R(S) P_2$, iff

$$(3.4) \quad R \in P_1 \text{ and}$$

$$(3.5) \quad \text{for each } y \in S(P_2), \exists \text{ an } x \in S(P_1) \text{ such that } x_i > y_i \forall i \in R.$$

Intuitively, if $P_1 \text{ dom}_R(S) P_2$, then the players in subset R prefer P_1 to P_2 because by Condition (3.5), no matter how the players disburse the payoffs corresponding to c.s. P_2 , each player in R will do better in c.s. P_1 . Condition (3.4) is imposed for the same reasons Condition (3.3) is imposed in Definition 3.2.

Definition 3.6. Let $P_1, P_2 \in \Pi(S)$ and S be a p.s.c. P_1 dominates P_2 w.r.t. S , denoted by $P_1 \text{ dom}(S) P_2$, iff

$$(3.6) \quad \exists \text{ a nonempty } R \in 2^N \text{ such that } P_1 \text{ dom}_R(S) P_2.$$

We now have another abstract game $(\Pi(S), \text{dom}(S))$ where $\Pi(S)$ is the set of outcomes and $\text{dom}(S)$ is the binary relation on $\Pi(S)$. Once again we look at the core and the dynamic solution of this abstract game.

Definition 3.7. Let Γ be an n-person cooperative game and S be a p.s.c. The core of coalition structures w.r.t. p.s.c. S , denoted by $K_0(S)$, is the core of the abstract game $(\Pi(S), \text{dom}(S))$.

Definition 3.8. Let Γ be an n-person cooperative game and S be a p.s.c. The dynamic solution of coalition structures w.r.t. p.s.c. S , denoted by $K_1(S)$, is the dynamic solution of the abstract game $(\Pi(S), \text{dom}(S))$.

Once again, by appealing to Proposition 2.3, we have:

Proposition 3.3. $K_0(S) \subset K_1(S)$.

Also, since $\Pi(S)$ is always finite, we have:

Proposition 3.4. $K_1(S) \neq \emptyset$.

The following results gives a comparison of the two models.

Theorem 3.5. Let Γ be an n-person cooperative game and S be a p.s.c. Then we have

$$K_0(S) \supset \{P \in \Pi: (x, P) \in J_0(S)\}.$$

Proof: Let $P_1 \in \{P \in \Pi: (x, P) \in J_0(S)\}$. Then $\exists x \in S(P_1)$ such that (x, P_1) is undominated in $SC(S)$ which implies that P_1 is undominated (w.r.t. S) in $\Pi(S)$, i.e., $P_1 \in K_0(S)$. \square

Another consequence of the definitions of $K_0(S)$ and $J_0(S)$ is as follows:

Theorem 3.6. Let Γ be an n -person cooperative game and S be a p.s.c. such that $\forall P \in \Pi$, $S(P)$ is either a single point set in E^n or an empty set. Then

$$K_0(S) = \{P \in \Pi: (x, P) \in J_0(S)\} \text{ and}$$

$$J_0(S) = \{(S(P), P): P \in K_0(S)\}.$$

If $J_0(S) \neq \emptyset$, then the solution configuration model indicates both coalition structures and distribution of payoffs among the players as solutions in $J_0(S)$ whereas the coalition structure model indicates only coalition structures as solutions in $K_0(S)$. Also by Theorem 3.5, $J_0(S)$ indicates fewer (or at most an equal number of) coalition structures as solutions compared to $K_0(S)$. However, if the p.s.c. S is such that for each $P \in \Pi$, $S(P)$ is either a single point in E^n or an empty set, then the two models are identical (except in form) and indicate the same results.

4. Representation by Digraphs

Since the number of coalition structures is finite, we can represent the abstract game $(\Pi(S), \text{dom}(S))$ of a game on N by means of a directed graph (or digraph). Given a payoff solution concept S , let $D = D(S)$ be a digraph whose vertex set $V(D) = \Pi(S)$ and whose arc set $A(D)$ is given by

$$(4.1) \quad A(D) = \{(P_1, P_2) \in \Pi(S) \times \Pi(S): P_1 \text{ dom}(S) P_2\}.$$

We call such a digraph D the domination digraph of the abstract game $(\Pi(S), \text{dom}(S))$.

Example 4.1. Let Γ be a 3-person game on $\{1,2,3\}$. Let S be a p.s.c. defined as follows:

Let $0 \leq a \leq b \leq c = d$ be real numbers such that $c > a+b$ and

$$S(P) = \begin{cases} (0,0,0) & \text{if } P = \{\{1\}, \{2\}, \{3\}\} \\ (0,a,0) & \text{if } P = \{\{1,2\}, \{3\}\} \\ (0,0,b) & \text{if } P = \{\{1,3\}, \{2\}\} \\ \{(0, x_2, c-x_2) : a \leq x_2 \leq c-b\} & \text{if } P = \{\{1\}, \{2,3\}\} \text{ or } \{\{1,2,3\}\} \end{cases}$$

To condense notation, we shall drop the braces around coalitions in coalition structures and, for example, denote $\{\{1\}, \{2,3\}\}$ by $(1)(23)$.

Note that

$$(1)(23) \text{ dom}(S) (1)(2)(3),$$

$$(1)(23) \text{ dom}(S) (12)(3),$$

$$(1)(23) \text{ dom}(S) (13)(2).$$

The domination graph of the game Γ is shown in Figure 4.1.

Let $(P_1, P_2) \in A(D)$. Then we say P_1 is adjacent to P_2 and P_2 is adjacent from P_1 . The outdegree, $\text{od}(P)$, for $P \in \Pi(S)$ is the number of c.s.'s adjacent from it and the indegree, $\text{id}(P)$, for $P \in \Pi(S)$ is the number adjacent to it. Then, in terms of this terminology, the core of the abstract game $(\Pi(S), \text{dom}(S))$ is given by

$$(4.2) \quad K_0(S) = \{P \in V(D) : \text{id}(P) = 0\}.$$

In Example 4.1, $K_0(S) = \{(1)(23), (123)\}$.

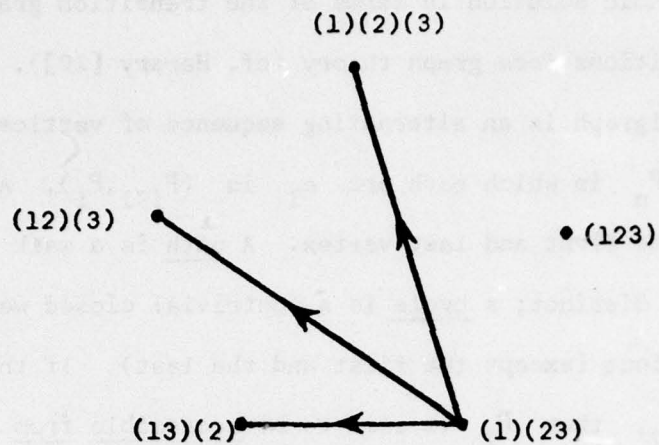


Figure 4.1. The domination digraph of game in Example 4.1.

The converse digraph D' of D has the same vertex set as D and the arc $(P_1, P_2) \in A(D') \iff (P_2, P_1) \in A(D)$. Thus the converse of D is obtained by reversing the direction of every arc in D . If $D = D(S)$ is the domination digraph of the abstract game $(\Pi(S), \text{dom}(S))$, then we call its converse $D' = D'(S)$ the transition digraph of the abstract game $(\Pi(S), \text{dom}(S))$. The transition digraph of the game in Example 4.1 is shown in Figure 4.2.

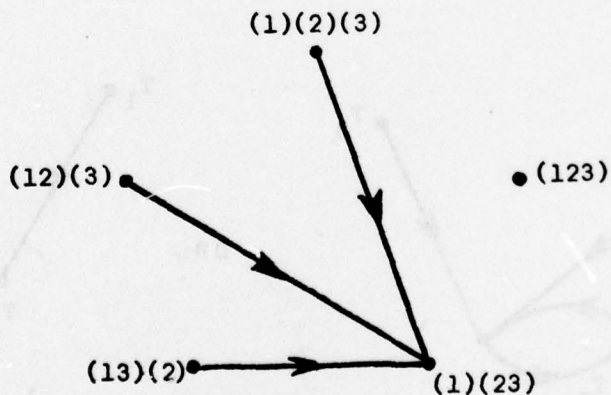


Figure 4.2. The transition digraph of the game in Example 4.1.

To define the dynamic solution in terms of the transition graph, we need a few basic definitions from graph theory (cf. Harary [10]). A (directed) walk in a digraph is an alternating sequence of vertices and arcs $p_0, e_1, p_1, \dots, e_n, p_n$ in which each arc e_i is (p_{i-1}, p_i) . A closed walk has the same first and last vertex. A path is a walk in which all vertices are distinct; a cycle is a nontrivial closed walk with all vertices distinct (except the first and the last). If there is a path from p_1 to p_2 , then p_2 is said to be accessible from p_1 . A digraph is strongly connected or strong if any two vertices are mutually accessible. A strong component of a digraph is a maximal strong subgraph. Let T_1, T_2, \dots, T_m be the strong components of D . The condensation D^* of D has the strong components of D as its vertices, with an arc from T_i to T_j whenever there is at least one arc in D from a vertex of T_i to a vertex of T_j . (See Figure 4.3.) It follows from the maximality of strong components that the condensation D^* of any graph D has no cycles. Let $D'(S)$ be the transition graph of the abstract game $(\Pi(S), \text{dom}(S))$ with strong components T_1, T_2, \dots, T_m .

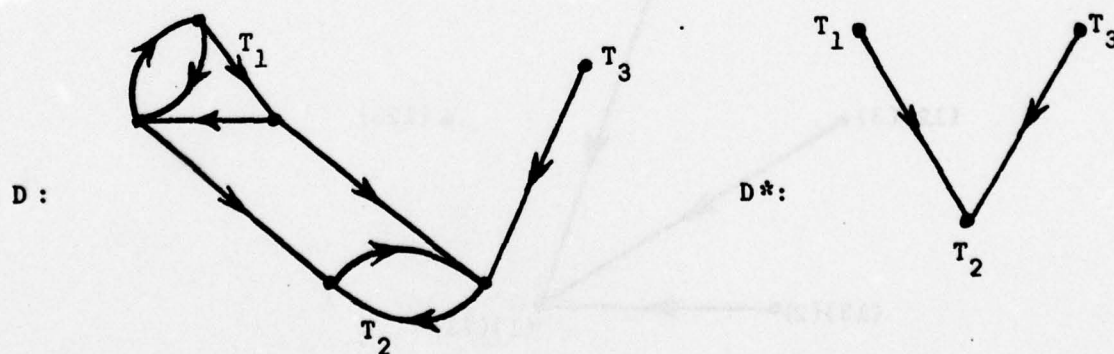


Figure 4.3. A digraph and its condensation.

Then the dynamic solution of the abstract game is given by

$$(4.3) \quad K_1(S) = \cup \{T_i : \text{od}(T_i) = 0 \text{ in the condensation } D^*\}.$$

In Example 4.1, $K_1(S) = \{(1)(23), (123)\}$.

5. Solutions with Respect to the Individually Rational Payoffs

In the next four sections, we will characterize the solutions of the abstract games for the special case of games with side payments using various payoff solution concepts.

A cooperative n-person game in characteristic function form with side payments is a pair (N, v) where $N = \{1, \dots, n\}$ denotes the set of players (as stated before) and v is a nonnegative real-valued function defined on the subsets of N which satisfies $v(\emptyset) = 0$ and $v(\{i\}) = 0$ for[†] all $i \in N$.

The individually rational payoffs (i.r.p.) corresponding to coalition structure $P = (P_1, \dots, P_m) \in \Pi$ is the set

$$I(P) = \{x \in E^n : \sum_{i \in P_j} x_i = v(P_j) \text{ for all } j = 1, \dots, m \text{ and } x_i \geq v(i) \text{ for}^\ddagger \text{ all } i \in N\}.$$

[†] This condition and the nonnegativity restriction on v causes no real loss of generality since all the payoff solution concepts we consider are invariant under strategic equivalence.

[‡] To condense notation, we shorten expressions like $v(\{i, j, k\})$ to $v(ijk)$ and so on.

When $P = (N)$, $I((N))$ is also referred to as the set of imputations.

Since $I(P)$ is nonempty for all $P \in \Pi$, we have

$$\Pi(I) = \Pi.$$

A game (N, v) is said to be superadditive if

$$(5.1) \quad R_1 \cap R_2 = \emptyset, \quad R_1, R_2 \in 2^N \Rightarrow v(R_1) + v(R_2) \leq v(R_1 \cup R_2)$$

and strictly superadditive if strict inequality holds in Relation (5.1).

Define the worth of a coalition structure P in the game (N, v)

by

$$(5.2) \quad w(P) = \sum_{P_j \in P} v(P_j).$$

Let

$$(5.3) \quad z = \max_{P \in \Pi} w(P)$$

and define

$$(5.4) \quad \Pi_z = \{P \in \Pi: w(P) = z\}.$$

If $x \in E^N$ and $R \subset N$, let $x(R)$ denote $\sum_{i \in R} x_i$. Then we have the following theorem.

Theorem 5.1. Let Γ be an n -person cooperative game with side payments.

Then $K_0(I) \neq \emptyset$. In particular, we have $K_0(I) \supset \Pi_z$.

Proof. Let $P^1 = (P_1^1, P_2^1, \dots, P_m^1) \in \Pi_z$. Suppose $\exists P \in \Pi$ such that $P \text{ dom}(I) P^1$, i.e. $\exists R \in P$ such that $P \text{ dom}_R(I) P^1$. Now we can

write $R = \bigcup_{i=1}^m (R \cap P_i^1)$. Pick $y \in I(P^1)$ such that $y(R \cap P_i^1) = v(P_i^1)$ if $R \cap P_i^1 \neq \emptyset$ for all $i = 1, 2, \dots, m$. Since $P \text{ dom}_R(I) P^1$, $\exists x \in I(P)$ s.t. $x_i > y_i$ for all $i \in R$. I.e. $v(R) = x(R) > y(R) = \sum_{P_i^1 \cap R \neq \emptyset} v(P_i^1)$. Pick $P^2 \in \Pi$ as follows. $P^2 = \{R\} \cup \{P_i^1 - \{P_i^1 : P_i^1 \cap R \neq \emptyset\}\} \cup \{P_i^1 - R : P_i^1 \cap R \neq \emptyset\}$. Then $w(P^2) > w(P^1)$, a contradiction! This completes the proof. \square

The following example will show that, in general, we cannot make a stronger statement than in the theorem above.

Example 5.1. Let Γ be a 4-person game with

$$v(12) = v(34) = v(23) = 1, \text{ and } v(R) = 0 \text{ for all other } R \subset N.$$

Let $P_1 = (12)(34)$, $P_2 = (14)(23)$ and $P_3 = (1)(23)(4)$. $w(P_1) = 2$, $w(P_2) = w(P_3) = 1$. But $K_0(I) = \{P_1, P_2, P_3\}$.

However, with a slight assumption, we can claim the following.

Theorem 5.2. Let Γ be an n -person game with side payments such that $(N) \in \Pi_z$. Then $K_0(I) = \Pi_z$.

Proof: From Theorem 5.1 we need prove only $K_0(I) \subset \Pi_z$. Let $P_1 \in \Pi$ such that $P_1 \notin \Pi_z$, i.e. $w(P_1) < z$. Then $(N) \text{ dom}(I) P_1$. This is seen as follows. Let $x \in I(P_1)$. Then $x(N) = w(P_1) < z$. Define y so that $y_i = x_i + (z - w(P_1))/n$ for all $i \in N$. Then $y \in I(\{N\})$ and $y_i > x_i$ for all $i \in N$. \square

Corollary 5.3. Let Γ be a superadditive game. Then $K_0(I) = \Pi_z$. Furthermore, if Γ is strictly superadditive, then $K_0(I) = \{(N)\}$.

Proof: Γ superadditive $\Rightarrow (N) \in \Pi_z$, and Γ strictly superadditive $\Rightarrow \Pi_z = \{(N)\}$. \square

For the solution configurations model, no general existence result is possible as is illustrated by the following example:

Example 5.2. Let $\Gamma = (N, v)$ be a 3-person game with

$$v(12) = v(13) = v(23) = 2, \quad v(123) = 2.5.$$

It can easily be shown that for this game $J_0(I) = \emptyset$.

6. Solutions with Respect to the Core

Let (N, v) be a cooperative game with side payments. Then the core of the game (N, v) corresponding to c.s. $P \in \Pi$ is defined by

$$(6.1) \quad \text{Co}(P) = \{x \in I(P) : x(R) \geq v(R) \text{ for all } R \in 2^N\}.$$

The core corresponding to a particular c.s. may be empty. Hence in general $\Pi(\text{Co}) \neq \Pi$. In fact, for some games the core corresponding to every c.s. may be empty, i.e., $\Pi(\text{Co}) = \emptyset$. A characterization of $K_0(\text{Co})$ and $J_0(\text{Co})$ is as follows.

Theorem 6.1. Let (N, v) be a cooperative game with side payments. Then,

$$K_0(\text{Co}) = \Pi(\text{Co}) = \{P : \text{Co}(P) \neq \emptyset\}.$$

Also

$$J_0(\text{Co}) = \text{SC}(\text{Co}) = \bigcup_{P \in \Pi(\text{Co})} [\text{Co}(P) \times \{P\}].$$

Proof: Let $P_1, P_2 \in \Pi(\text{Co})$. Suppose $P_1 \text{ dom}_R(\text{Co}) P_2$ for some $R \in P_1$. Let $y \in \text{Co}(P_2)$. Then $\exists x \in \text{Co}(P_1)$ s.t. $x_i > y_i$ for all $i \in R$. I.e. $x(R) > y(R)$. But since $R \in P_1$, $x(R) = v(R)$. Hence $y(R) < v(R)$ contradicting the fact that $y \in \text{Co}(P_2)$. The proof of the second assertion is similar to the first. \square

Corollary 6.2. Let (N, v) be a cooperative game with side payments. Let S be a p.s.c. such that, for all $P \in \Pi$, $S(P) \subset I(P)$, and $S(P) \cap \text{Co}(P) \neq \emptyset$ whenever $\text{Co}(P) \neq \emptyset$. Then $K_0(\text{Co}) \subset K_0(S)$ and $J_0(\text{Co}) \subset J_0(S)$ (as subsets of Π).

In light of Theorem 6.1 we would like to characterize the coalition structures with nonempty cores. The next two theorems along with a known characterization of games with nonempty cores corresponding to the grand coalition N accomplish this task.

Theorem 6.3. Let (N, v) be a cooperative game with side payments. If $\Pi(\text{Co}) \neq \emptyset$, then $\Pi(\text{Co}) = \Pi_z$.

Proof: Let $P_1 \in \Pi(\text{Co})$, and suppose $P_1 \notin \Pi_z$. Then $\exists P_2 \in \Pi$ such that $w(P_2) > w(P_1)$. Let $x \in \text{Co}(P_1)$. Then $x(R) \geq v(R)$ for all $R \subset N$ which implies that $w(P_1) = x(N) \geq w(P_2)$ and this is a contradiction! Hence $\Pi(\text{Co}) \subset \Pi_z$.

Let $P_1 \in \Pi_z$ and assume $P_2 \in \Pi(\text{Co}) \subset \Pi_z$. Let $x \in \text{Co}(P_2)$. Then $x(R) \geq v(R)$ for all $R \subset N$. If $x(P) > v(P)$ for some $R \in P_1$, then $w(P_2) = x(N) > w(P_1)$, contradicting the fact that $P_1 \in \Pi_z$. Hence $x(P) = v(P)$ for all $P \in P_1 \Rightarrow x \in \text{Co}(P_1) \Rightarrow P_1 \in \Pi(\text{Co})$. Therefore $\Pi(\text{Co}) \supset \Pi_z$. \square

Corollary 6.4. Let (N, v) be a game with side payments. Then for all $P_1, P_2 \in \Pi(\text{Co})$, $\text{Co}(P_1) = \text{Co}(P_2)$.

Corollary 6.5. Let (N, v) be a game with side payments. If there is a $P \in \Pi_z$ such that $\text{Co}(P) = \emptyset$, then $\Pi(\text{Co}) = \emptyset$.

Given a game $\Gamma = (N, v)$ define a game $\Gamma_z = (N, v_z)$ derived from Γ as follows.

$$(6.2) \quad v_z(R) = \begin{cases} z & \text{if } R = N \\ v(R) & \text{for all other } R \subset N \end{cases}$$

where $z = \max_{P \in \Pi} w(P)$.

When there is more than one game under discussion, we shall denote the sets $\text{Co}(P)$, $\Pi(\text{Co})$ and Π_z by $\text{Co}(P, \Gamma)$, $\Pi(\text{Co}, \Gamma)$, and $\Pi_z(\Gamma)$, respectively.

Theorem 6.6. Let $\Gamma = (N, v)$ be a game and Γ_z be as in Relation (6.2). Then if $\text{Co}(P, \Gamma) \neq \emptyset$, $\text{Co}(P, \Gamma) = \text{Co}((N), \Gamma_z)$.

Proof: From the definition of Γ_z it is clear that for $P \neq (N)$ $\text{Co}(P, \Gamma) = \text{Co}(P, \Gamma_z)$. From Theorem 6.3 we obtain $\Pi(\text{Co}, \Gamma_z) = \Pi_z(\Gamma_z)$. Since $(N) \in \Pi_z(\Gamma_z)$, by Corollary 6.4, $\text{Co}(P, \Gamma_z) = \text{Co}((N), \Gamma_z)$. Hence the theorem follows. \square

Games with nonempty cores corresponding to the grand coalition have been characterized by Bondareva [4,5] and Shapley [19]. For the sake of completeness we will repeat this characterization here.

A balanced set B is defined to be a collection of subsets R of N with the property that there exist positive numbers $\delta_R \forall R \in B$

called weights, such that for each $i \in N$ we have

$$(6.3) \quad \sum_{\{R \in B: i \in R\}} \delta_R = 1.$$

A game (N, v) is called balanced iff

$$(6.4) \quad \sum_{R \in B} \delta_R v(R) \leq v(N)$$

holds for every balanced set with weights $\{\delta_R\}$. The following theorem was proved by Bondareva [4,5] and Shapley [19].

Theorem 6.7. Let (N, v) be a game. Then $\text{Co}((N)) \neq \emptyset$ if and only if the game is balanced.

Corollary 6.8. Let $\Gamma = (N, v)$ be a game. Then $\Pi(\text{Co}, \Gamma) \neq \emptyset$ if and only if the game (N, v_z) is balanced.

Proof: (Necessity): $\Pi(\text{Co}, \Gamma) \neq \emptyset \Rightarrow \text{Co}((N), (N, v_z)) \neq \emptyset$ (by Theorem 6.6) $\Rightarrow (N, v_z)$ is balanced (by Theorem 6.7).

(Sufficiency): If $\Gamma_z = (N, v_z)$ is balanced $\Rightarrow \text{Co}((N), \Gamma_z) \neq \emptyset$ (by Theorem 6.7). If $(N) \in \Pi_z(\Gamma)$ then $\Gamma = \Gamma_z$ and we are finished.

Otherwise $\exists P \in \Pi_z(\Gamma_z)$ such that $P \neq (N)$. Then, $\text{Co}(P, \Gamma) = \text{Co}(P, \Gamma_z) = \text{Co}((N), \Gamma_z) \neq \emptyset$. \square

Thus we have completely characterized $K_0(\text{Co})$ and $J_0(\text{Co})$ for all games with side payments.

Example 6.1. (A game with no solution. See Lucas [13,14].)

Let $N = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$ and v be given by

$$\begin{aligned}
v(N) &= 5, \quad v(13579) = 4, \\
v(12) &= v(34) = v(56) = v(78) = v(910) = 1, \\
v(3579) &= v(1579) = v(1379) = 3, \\
v(357) &= v(157) = v(137) = 2, \\
v(359) &= v(159) = v(139) = 2, \\
v(1479) &= v(3679) = v(5279) = 2, \quad \text{and} \\
v(R) &= 0 \quad \text{for all other } R \subset N.
\end{aligned}$$

In this game $z = 5$, $\Pi_z = \{(N), P_1 = (12)(34)(56)(78)(910)\}$ and $\text{Co}((N)) = \text{Co}(P_1) = \{x: x(12) = x(34) = x(56) = x(78) = x(910) = 1, \text{ and } x(13579) \geq 4\}$. By Theorem 6.1,

$$K_0(\text{Co}) = \{(N), P_1\}, \quad \text{and}$$

$$J_0(\text{Co}) = \text{Co}((N)) \times \{(N), P_1\}.$$

7. Solutions with Respect to the Shapley Value

Shapley [17] defined a unique value satisfying three axioms for all n -person cooperative games with side payments. It was assumed that the grand coalition would form. Later, Aumann and Dreze [2] generalized the axioms to define the Shapley value for all coalition structures.

A permutation α of N is a one-one function from N onto itself. For $R \in 2^N$, write $\alpha R = \{\alpha i: i \in R\}$. If v is a game on N , define a game $\alpha * v$ on N by

$$(7.1) \quad (\alpha * v)(R) = v(\alpha R) \quad \text{for all } R \in 2^N.$$

Also, if v and u are games on N , define a game $v+u$ on N by

$$(7.2) \quad (v+u)(R) = v(R) + u(R) \quad \text{for all } R \in 2^N.$$

Call a c.s. $P = (P_1, \dots, P_m)$ invariant under α if $\alpha P_j = P_j$ for all $j = 1, \dots, m$. Player i is null if $v(R \cup \{i\}) = v(R)$ for all $R \in 2^N$.

Let G^N denote the set of all games with side payments on N . Since we assume that for all games with side payments, $v(\emptyset) = 0$ and $v(i) = 0 \forall i \in N$, G^N is a Euclidean space of dimension $2^n - (n+1)$.

Fix $N = \{1, \dots, n\}$ and $P = (P_1, \dots, P_m) \in \Pi$. The Shapley value corresponding to c.s. P is a function ϕ_P from G^N to E^n i.e. a function that associates with each game a payoff vector satisfying the following axioms:

A.1 (Relative Efficiency): $\phi_P(v)(P_j) = v(P_j)$ for all $j = 1, \dots, m$.

A.2 (Symmetry): For all permutations α of N under which P is invariant,

$$\phi_P(\alpha * v)(R) = \phi_P(v)(\alpha R).$$

A.3 (Additivity): $\phi_P(v+u) = \phi_P(v) + \phi_P(u)$.

A.4 (Null Player Axiom): If i is a null player, then $\phi_P(v)(i) = 0$.

When $P = (N)$, the above axioms are equivalent to Shapley's axiom which specify a unique value $\phi(v) = (\phi_1(v), \dots, \phi_n(v))$ given by

$$(7.3) \quad \phi_i(v) = \phi_{(N)}(v)(i) = \sum_{R \subset N} \frac{(r-1)!(n-r)!}{n!} [v(R) - v(R - \{i\})]$$

where $r = |R|$, the cardinality of coalition R . For each $R \in 2^N$, denote by $v|_R$ the game on R defined for all $T \subset R$ by

$$(7.4) \quad (v|R)(T) = v(T).$$

Theorem 7.1. Fix N and $P = (P_1, \dots, P_m)$. Then there is a unique value ϕ_P and it is given for all $j = 1, \dots, m$ and $i \in P_j$ by

$$(7.5) \quad (\phi_P v)(i) = (\phi_{(P_j)}(v|P_j))(i).$$

Proof: See Aumann and Dreze [2, pp. 220-221].

Since $\phi(P)^\dagger$ is nonempty for all $P \in \Pi$, $\Pi(\phi) = \Pi$. Also note from (7.3) that if v is superadditive, then $\phi(P)(i) \geq 0$ and hence $\phi(P) \in I(P)$. Also, since $\phi(P)$ consists of a unique outcome for all $P \in \Pi$, by Theorem 3.6 the s.c. model and the c.s. model give identical results. For convenience, all the results in this section are stated only for the c.s. model.

A partial existence theorem for $K_0(\phi)$ is as follows:

Theorem 7.2. Let Γ be an n -person game in which the only coalitions with positive values are all the $(n-1)$ -person and n -person coalitions. Then $K_0(\phi) \neq \emptyset$.

Proof: Let us denote the game as follows:

$$\begin{aligned} v(i) &= 0 \quad \text{for all } i \in N, \\ v(N - (i)) &= a_i \quad \text{for all } i \in N, \\ v(N) &= b, \quad \text{and } v(R) = 0 \quad \text{for all other } R \subset N. \end{aligned}$$

[†]When there is no doubt about the game v under consideration, we shall denote $\phi_P(v)$ by $\phi(P)$ which is consistent with the previous section.

We can assume (by relabelling of the players) that

$$(7.6) \quad a_1 \leq a_2 \leq \dots \leq a_n.$$

Let $a = \sum_{i=1}^n a_i$ and $\Pi_{a_n} = \{P \in \Pi: w(P) = a_n\}$. Using (7.3) and (7.5) we have

$$(7.7) \quad \phi((N))(i) = ((n-1)b + a - n \cdot a_i)/(n(n-1)).$$

By (7.6) we have

$$(7.8) \quad \phi((N))(1) \geq \phi((N))(2) \geq \dots \geq \phi((N))(n)$$

Also,

$$(7.9) \quad \phi((N-i)(i))(j) = \begin{cases} a_i/(n-1) & \text{for } j = 1, \dots, n \\ & j \neq i \\ 0 & \text{for } j = i \end{cases}$$

Clearly, the only c.s.'s we need look at are (N) and $(N-i)(i)$ for $i = 1, \dots, n$. All the c.s.'s not in Π_{a_n} (except (N)) are dominated by c.s.'s in Π_{a_n} . From Expressions (7.7), (7.8) and (7.9) it follows that $(N) \text{ dom}(\phi) (N-n)(n)$ iff

$$\phi((N))(n-1) > \phi((N-n)(n))(n-1)$$

i.e. iff

$$b > (n(a_n + a_{n-1}) - a)/(n-1).$$

Also if $a_n = a_{n-1}$ (i.e. $(N - (n-1))(n-1) \in \Pi_{a_n}$) then

$$(N) \text{ dom}(\phi) (N - (n-1))(n-1)$$

iff

$$\phi((N))(n) > \phi((N - (n-1))(n-1))(n),$$

i.e. iff

$$b > (n(a_n + a_{n-1}) - a)/(n-1).$$

Now,

$$(N-n)(n) \text{ dom}(\phi) (N)$$

iff

$$\phi((N-n)(n))(1) > \phi((N))(1),$$

i.e. iff

$$b < (n(a_n + a_1) - a)/(n-1).$$

Hence we have

$$K_0(\Phi) = \begin{cases} (N) & \text{If } b > (n(a_n + a_{n-1}) - a)/(n-1) \\ \Pi_{a_n} & \text{if } b < (n(a_n + a_1) - a)/(n-1) \\ (N) \cup \Pi_{a_n} & \text{otherwise.} \end{cases} \quad \square$$

Corollary 7.3. Let Γ be a 3-person game with side payments. Then $K_0(\Phi) \neq \emptyset$.

In general, this is the strongest existence result we can obtain. I.e. there is a 4-person game for which $K_0(\Phi) = \emptyset$. This is shown in Example 7.5.

If $\text{Co}(P) \neq \emptyset$, $\Phi(P)$ may not belong to $\text{Co}(P)$. Hence Corollary 6.2. is not applicable for the Shapley value. The following example illustrates this fact.

Example 7.1. Let $N = \{1, 2, 3\}$ and v be given by $v(1) = v(2) = v(3) = 0$, $v(12) = 50$, $v(13) = 50$, $v(23) = 56$, and $v(123) = 80$. Then the Shapley value is given by:

$$\Phi(P) = \begin{cases} (24.67, 27.67, 27.67) & \text{if } P = (123) \\ (0, 28, 28) & \text{if } P = (1)(23) \\ (25, 0, 25) & \text{if } P = (13)(2) \\ (25, 25, 0) & \text{if } P = (12)(3) \\ (0, 0, 0) & \text{if } P = (1)(2)(3) \end{cases}$$

Note that $\text{Co}((123)) = \text{Conv}\{(20, 30, 30), (24, 26, 30), (24, 30, 26)\}$ but $\Phi((123)) \notin \text{Co}((123))$. The transition digraph is shown in Figure 7.1, and hence $K_0(\Phi) = K_1(\Phi) = (1)(23)$.

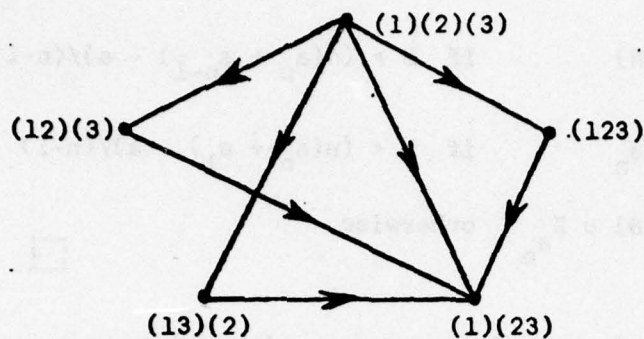


Figure 7.1. The transition digraph for Example 7.1.

The above example illustrates a weakness of the Shapley value in that the Shapley value is derived entirely from the characteristic function rather than the bargaining positions of the players in the process of coalition formation. However, the Shapley value has been extensively used as an a priori measure of power of players in "simple" games. Hence the study of $K_0(\Phi)$ and $K_1(\Phi)$ is most appropriate for simple games.

The class of all simple games forms a subclass of the class of all cooperative games with side payments. A simple game is a game in which every coalition has value either 1 or 0. A coalition $R \subset N$ is winning if $v(R) = 1$ and losing if $v(R) = 0$. A simple game can be represented by a pair (N, \mathcal{W}) where N is the set of players and \mathcal{W} is the set of winning coalitions. A simple game is monotonic iff $R \in \mathcal{W}$ and $T \supset R \Rightarrow T \in \mathcal{W}$, and superadditive (or proper) iff $R \in \mathcal{W} \Rightarrow N - R \notin \mathcal{W}$. Superadditivity implies monotonicity in simple games. A winning coalition R is called minimal winning if every proper subset of R is losing. A monotonic simple game can be represented by the pair (N, \mathcal{W}^m) where \mathcal{W}^m is the set of all minimal winning coalitions. If $\mathcal{W}^m = \{\{i\}\}$, then player i is said to be a dictator. If $j \in n \setminus \mathcal{W}^m \neq \emptyset$, then player j

is said to be a veto player. If $k \notin \cup \omega^m$ then player k is said to be a dummy. Dummies play no active role in the game and for all practical purposes can be omitted from the set of players. A weighted majority game is a monotonic simple game that can be represented by

$$(7.10) \quad [q; a_1, a_2, \dots, a_n]$$

where $q \geq 0$ is called the quota, $a_i \geq 0$, $i = 1, \dots, n$ is the weight of the i^{th} player, and $R \in \omega \iff \sum_{i \in R} a_i \geq q$. Expression (7.10) is said to be a weighted majority representation of the simple game. Two weighted majority representations are said to be equivalent if they represent the same simple game. E.g. $[2; 1, 1, 1]$ and $[5; 2, 3, 4]$ are equivalent since both represent the game $(\{1, 2, 3\}, \omega^m = \{(12), (13), (23)\})$. Not every monotonic simple game may have a weighted majority representation (see Shapley [18]).

Example 7.2. The most common of all simple games is the straight majority game M_n , n odd, in which

$$\omega^m = \{R \subset N: |R| = (n+1)/2\}$$

where $|R|$ denotes the cardinality of coalition R . The Shapley value is given by

$$\phi(P)(i) = \begin{cases} 1/|R| & \text{if } i \in R \in \omega, R \in P \\ 0 & \text{otherwise.} \end{cases}$$

It is clear that

$K_1(\phi) = K_0(\phi) = \{P \in \Pi: P \text{ contains a minimal winning coalition}\}.$

Example 7.3. The pure bargaining game B_n , is given by $\omega^m = \{(N)\}.$

The Shapley value is given by

$$\phi(P)(i) = \begin{cases} 1/n & \text{if } P = (N) \\ 0 & \text{otherwise} \end{cases}$$

clearly, $K_1(\phi) = K_0(\phi) = \{(N)\}.$

Example 7.4. Let Γ be a proper game with a dictator. Then

$$\phi(P)(i) = \begin{cases} 1 & \text{if } i \text{ is a dictator} \\ 0 & \text{otherwise.} \end{cases}$$

Hence $K_1(\phi) = K_0(\phi) = \Pi.$ Note that every player who is not a dictator is a dummy. So essentially we have a 1-person game in which the only player is winning by himself.

Example 7.5. Consider the weighted majority game $[3; 2,1,1,1].$ The minimal winning coalitions are $\omega^m = \{(12), (13), (14), (234)\}.$ The Shapley value is given by

$$\phi(P) = \begin{cases} (1/2, 1/6, 1/6, 1/6) & \text{if } P = (1234) \\ (2/3, 1/6, 1/6, 0) & \text{if } P = (123)(4) \\ (2/3, 1/6, 0, 1/6) & \text{if } P = (124)(3) \\ (2/3, 0, 1/6, 1/6) & \text{if } P = (134)(2) \\ (1/2, 1/2, 0, 0) & \text{if } P = (12)(34) \text{ or } (12)(3)(4) \\ (1/2, 0, 1/2, 0) & \text{if } P = (13)(24) \text{ or } (13)(2)(4) \\ (1/2, 0, 0, 1/2) & \text{if } P = (14)(23) \text{ or } (14)(2)(3) \\ (0, 1/3, 1/3, 1/3) & \text{if } P = (1)(234) \\ (0, 0, 0, 0) & \text{otherwise.} \end{cases}$$

The transition digraph of the game is shown in Figure 7.2. Since all c.s.'s that contain only losing coalitions are dominated, these are omitted from this transition digraph. Note that $K_0(\phi) = \emptyset$. However,

$$K_1(\phi) = \{(1)(234), (12)(3)(4), (12)(34), (134)(2), (13)(24), (13)(2)(4), (124)(3), (14)(23), (14)(2)(3), (123)(4)\}.$$

A closer look at the Shapley value for different c.s.'s in Example 7.5 reveals the following observation. If players 1 and 2 who are in a winning coalition with 3 in the c.s. $(123)(4)$ decide to expel player 3 from the coalition and form the smaller winning coalition (12) , one would expect both players not to decrease their power in the smaller winning coalition (12) since there are fewer players to share the same amount of power. However, player 1 actually does decrease his power from $2/3$ to $1/2$. We shall call this phenomenon the paradox of smaller coalitions. To understand why this phenomenon occurs, let us look at Theorem 7.1. It states

The following result is a consequence of the above definition.

Theorem 7.4. Let Γ be a proper simple game that does not exhibit the paradox of smaller coalitions w.r.t. ϕ . Then $K_0(\phi) \neq \emptyset$.

Proof: Let $T \in \mathcal{W}^m$ such that $|T| \leq |R|$ for all $R \in \mathcal{W}^m$. Let $P \in \Pi$ be such that $T \in P$. Then $\phi(P)(i) = 1/|T|$ for all $i \in T$. Suppose $\exists P_1 \in \Pi$ such that $P_1 \text{ dom}_R(\phi) P$ for some $R \in P_1$, i.e., $\phi(P_1)(i) > \phi(P)(i)$ for all $i \in R$. Let R' be any minimal winning coalition contained in R , i.e. $R' \subset R$ and $R' \in \mathcal{W}^m$. Let $P_2 \in \Pi$ be such that $R' \in P_2$. Then since Γ does not exhibit the paradox, $\phi(P_2)(i) \geq \phi(P_1)(i)$ for all $i \in R'$. Also

$$\phi(P_2)(i) = \begin{cases} 1/|R'| & \text{if } i \in R' \\ 0 & \text{otherwise.} \end{cases}$$

Since Γ is proper, $R' \cap T \neq \emptyset$. Hence for all $i \in R' \cap T$, $1/|R'| = \phi(P_2)(i) \geq \phi(P_1)(i) > \phi(P)(i) = 1/|T|$, which is a contradiction (since $|R'| \geq |T|$)! \square

Let

$$(7.11) \quad t = \min_{R \in \mathcal{W}^m} |R|$$

and let

$$(7.12) \quad \Pi_t = \{P \in \Pi : P \text{ contains a winning coalition of size } t\}.$$

Then we obtain the following.

Corollary 7.5. Let Γ be a proper simple game that does not exhibit the paradox of smaller coalitions w.r.t. Φ . Then $K_0(\Phi) \supset \Pi_t$.

That in general we cannot strengthen the above result is shown by the following example.

Example 7.6. Let Γ be a 4-person game represented by $[4; 2, 2, 1, 1]$. The minimal winning coalitions are $\{(12), (134), (234)\}$. The Shapley value is given by

$$\Phi(P) = \begin{cases} (1/2, 1/2, 0, 0) & \text{if } P = (12)(34) \text{ or } (12)(3)(4) \\ (1/2, 1/2, 0, 0) & \text{if } P = (123)(4) \text{ or } (124)(3) \\ (1/3, 0, 1/3, 1/3) & \text{if } P = (134)(2) \\ (0, 1/3, 1/3, 1/3) & \text{if } P = (1)(234) \\ (1/3, 1/3, 1/6, 1/6) & \text{if } P = (1234) \end{cases}$$

Note that the game does not exhibit the paradox of smaller coalitions.

Also $t = 2$, and $\Pi_t = \{(12)(3)(4), (12)(34)\}$. However,

$K_0(\Phi) = \{(12)(3)(4), (12)(34), (123)(4), (124)(3)\}$. Observe that players 3 and 4 are dummies in the subgame on $\{1, 2, 3\}$ and $\{1, 2, 4\}$ respectively.

An interesting problem raised by Theorem 7.4 is to characterize the class of games that do not exhibit the paradox of smaller coalitions w.r.t. Φ . Let us look at symmetric games. A game (N, v) is called symmetric if the value of a coalition depends only on the size of the coalition. A symmetric monotonic simple game is of the type $M_{n,k} = (N, w)$

where $W = \{R \subset N: |R| \geq k\}$. The following proposition follows from the symmetry axiom of the Shapley value.

Proposition 7.6. Let Γ be a symmetric simple game. Then Γ does not exhibit the paradox of smaller coalitions w.r.t. Φ . In fact, $K_0(\Phi) = \Pi_t$.

Proof: The Shapley value is given by

$$\Phi(P)(i) = \begin{cases} 1/|R| & \text{if } i \in R \in P \text{ and } R \in W \\ 0 & \text{otherwise.} \end{cases}$$

Hence the result follows from Statement (7.5). \square

Since Example 7.6 does not exhibit the paradox and is not symmetric, Proposition 7.6 is not a complete characterization. A list of all proper simple games with four or fewer players is given in the appendix along with the Shapley value Φ corresponding to all coalition structures, $K_0(\Phi)$, and whether or not the game exhibits the paradox.

Another interesting problem is to determine, if possible, a power index that has all the desirable properties of the Shapley value but that does not exhibit the paradox of smaller coalitions.

The most critical axiom of the Aumann-Dreze generalization of the Shapley value is A.3.

A.3. $\Phi_P(v+u) = \Phi_P(v) + \Phi_P(u)$.

This axiom is acceptable if and only if we assume that the c.s. P is fixed

and that players in a coalition $P_k \in P$ cannot bargain on the basis of the values of coalitions not contained in P_k . This assumption is not appropriate for our model where the players are bargaining for a coalition structure and no c.s. is fixed.

Another generalization of the Shapley value (which he defined only for the grand coalition) to the case of all coalition structures which is appropriate for monotonic simple games is as follows.

- (i) The Shapley value corresponding to the grand coalition is used as an a priori measure of power of the players. This is suggested by Shapley and Shubik [20].
- (ii) And within any coalition in a c.s., a player can expect to share in the payoff proportional to his power as defined in (i). This is suggested by Gamson [8].

Assumptions (i) and (ii) define a unique value for all monotonic simple games which we denote by Φ' . We can define Φ' by axioms as follows:

The (generalized) Shapley value Φ' is a function from $\Pi \times G^N$ to E^n , i.e., a function that associates with each game and a c.s. a payoff vector satisfying the following axioms:

A'.1 (Relative Efficiency): $\Phi'(P, v)(P_k) = v(P_k)$ for all $P_k \in P$, and all $P \in \Pi$.

A'.2 (Symmetry): For all $P \in \Pi$, and all permutations α of N under which P is invariant,

$$\Phi'(P, \alpha * v)(R) = \Phi'(P, v)(\alpha R) \text{ for all } R \subset N.$$

A'.3 (Additivity): If v and u are games in G^N , then

$$\phi'((N), v+u) = \phi'((N), v) + \phi'((N), u)$$

A'.4 (Null Player Axiom): If i is a null player, then

$$\phi'(P, v)(i) = 0 \text{ for all } P \in \Pi.$$

A'.5 (Proportionality): For all $P \in \Pi$,

$$\phi'(P, v)(i) \cdot \phi'((N), v)(j) = \phi'(P, v)(j) \cdot \phi'((N), v)(i)$$

for all $i, j \in P_k \in P$.

When $P = (N)$, Axioms A'.1 - A'.4 are equivalent to Shapley's axioms which specify the unique value given by Expression (7.3). Denote $\phi'((N), v)$ by $\phi(v) = (\phi_1(v), \dots, \phi_n(v))$. (Since $\phi'((N), v) = \phi_{(N)}(v)$ our notation is consistent.) Next we obtain the following result.

Theorem 7.7. Fix $N = \{1, \dots, n\}$ and let G^N denote the set of all monotonic games on N . Then there is a unique value satisfying Axioms A'.1 - A'.5 given by Expression (7.3) and

$$(7.13) \quad \phi'(P, v)(j) = \begin{cases} \frac{\phi_j(v)}{\sum_{i \in P_k} \phi_i(v)} \cdot v(P_k) & \text{where } P_k \in P \text{ is such that} \\ & j \in P_k, \text{ if } j \text{ is not a null player} \\ 0 & \text{if } j \text{ is a null player} \end{cases}$$

Proof: It can be easily shown that Statements (7.3) and (7.13) satisfy Axioms A'.1 - A'.5. Uniqueness follows from Axioms A'.1 and A'.5. \square

Corollary 7.8. Let Γ be a monotonic simple game. Then Γ does not exhibit the paradox of smaller coalitions w.r.t. Φ' .

Proof: This follows from Expression (7.13).

In view of Corollary 7.5, we might be tempted to assert that $K_0(\Phi') \supset \Pi_t$. However, the following example shows that it is not true.

Example 7.7. Consider the weighted majority game given in Example 7.5 [3; 2,1,1,1]. Then Φ' is given by

$$\Phi'(P)^\dagger = \begin{cases} (3/6, 1/6, 1/6, 1/6) & \text{if } P = (1234) \\ (3/5, 1/5, 1/5, 0) & \text{if } P = (123)(4) \\ (3/4, 1/4, 0, 0) & \text{if } P = (12)(3)(4) \text{ or } (12)(34) \\ (0, 1/3, 1/3, 1/3) & \text{if } P = (1)(234). \end{cases}$$

For all other c.s.'s, $\Phi'(P)$ can be determined by the symmetry of players 2, 3, and 4. It is clear that $K_0(\Phi') = \{(1)(234)\}$. Note that in this example $t = 2$, hence $(1)(234) \notin \Pi_t$.

Let

$$(7.14) \quad s = \min_{R \in W^m} \sum_{i \in R} \phi_i(v),$$

[†]When there is no doubt about the game v under consideration, we shall denote $\Phi'(P, v)$ by $\Phi'(P)$ which is consistent with the established notation.

and let

$$(7.15) \Pi_s = \{P \in \Pi: P \text{ contains a coalition } R \text{ such that } \sum_{i \in R} \phi_i(v) = s\}.$$

Then we have the following important fact.

Theorem 7.9. Let Γ be a proper simple game. Then $K_0(\phi') = \Pi_s$.

Proof: Denote $\phi'((N))$ by $\phi = (\phi_1, \dots, \phi_n)$. Let $P_1 \in \Pi_s$. Suppose $P_2 \in \Pi$ such that $P_2 \text{ dom}_R(\phi') P_1$ for some $R \in P_2$ such that $R \in P$. Then $\phi'(P_2)(i) > \phi'(P_1)(i)$ for all $i \in R$. Let $T \in P_1$ be such that $T \in \omega^m$ and $\sum_{i \in T} \phi_i = s$. Since Γ is proper $R \cap T \neq \emptyset$. Pick $j \in R \cap T$. Then $\phi'(P_1)(j) = \phi_j/s$. Since $j \in R$, $\phi'(P_2)(j) = \phi_j / (\sum_{i \in R} \phi_i) > \phi_j/s$, i.e., $\sum_{i \in R} \phi_i < s$, a contradiction! Hence $K_0(\phi') \supset \Pi_s$.

Let $P_1 \in \Pi_s$ and $P_2 \in \Pi$ be such that $P_2 \not\in \Pi_s$. Then $P_1 \text{ dom}_T(\phi') P_2$ where $T \in P_1$ such that $T \in \omega^m$ and $\sum_{i \in T} \phi_i = s$ because $\phi(P_1)(i) = \phi_i/s$ for all $i \in T$ and $\phi'(P_2)(i) < \phi_i/s$ for all $i \in T$. Hence $K_0(\phi') \subset \Pi_s$. \square

8. Solutions with Respect to the Bargaining Set $M_1^{(i)}$

The bargaining set was first introduced by Aumann and Maschler [3]. They defined several types of bargaining sets. One of these, denoted by $M_1^{(i)}$, was shown to be nonempty for every c.s. by Peleg [16].

Let x^R denote a vector in E^R where $r = |R|$, whose elements are indexed by the players in R . Let $x \in I(P)$ and let i and j be two distinct players in coalition $P_k \in P$. An objection of i against j to $x \in I(P)$ is a vector y^R , where R is a coalition containing player i

but not j , whose coordinates y_ℓ satisfy $y_i > x_i$, $y_\ell \geq x_\ell \forall \ell \in R$ and $\sum_{\ell \in R} y_\ell = v(R)$. A counter-objection to this objection is a vector z^D , where D is a coalition containing player j but not i , whose coordinates z_ℓ satisfy $z_\ell \geq x_\ell$ for each $\ell \in D$, $z_\ell \geq y_\ell$ for each $\ell \in R \cap D$, and $\sum_{\ell \in D} z_\ell = v(D)$.

$x \in I(P)$ is stable if for each objection to x , there is a counter-objection. The bargaining set corresponding to the c.s. $P \in \Pi$, denoted by $M_1^{(i)}(P)$ is the set of all stable individually rational payoff $x \in I(P)$, i.e.,

$$(8.1) \quad M_1^{(i)}(P) = \{x \in I(P) : x \text{ is stable}\}.$$

Theorem 8.1. Let Γ be an n -person cooperative game with side payments. Then $M_1^{(i)}(P) \neq \emptyset$ for each $P \in \Pi$.

Proof. See Davis and Maschler [7] and Peleg [16].

As a result $\Pi(M_1^{(i)}) = \Pi$. The bargaining set is a natural payoff solution concept to study the solutions J_0 and K_0 for the following reasons:

- (i) the bargaining set for each c.s. consists of payoffs that are stable in the sense of objections and counter-objections. If for a particular c.s., a payoff is not in the bargaining set, some player would have a justified objection (an objection that has no counter-objection) which when carried out would result in breakup of the coalition structure. Hence we are not justified in using unstable payoffs corresponding to a c.s. to dominate another c.s. Also,
- (ii) the bargaining set is nonempty for each coalition structure.

We shall now determine $K_0(M_1^{(i)})$ for all 3-person games with side payments.

Consider the 3-person game given by $N = \{1,2,3\}$,

$$(8.2) \quad \begin{aligned} v(1) = v(2) = v(3) = 0, \quad v(12) = a, \quad v(13) = b, \quad v(23) = c, \\ \text{and } v(123) = d, \text{ where } 0 \leq a \leq b \leq c \text{ and } d \geq 0. \end{aligned}$$

Theorem 8.2. Let Γ be a 3-person game as in (8.2) with $d > (a+b+c)/2$.

- (i) If $d < c$, then $K_0(M_1^{(i)}) = \{(1)(23)\}$
- (ii) If $d = c$, then $K_0(M_1^{(i)}) = \{(1)(23), (123)\}$
- (iii) If $d > c$, then $K_0(M_1^{(i)}) = \{(123)\}$.

Proof: (i) In this case we have $(a+b)/2 + c/2 < d < c/2 + c/2$, hence $a+b < c$. The bargaining set is given by

$$(8.3) \quad M_1^{(i)}(P) = \begin{cases} (0, 0, 0) & \text{if } P = (1)(2)(3), \\ (0, a, 0) & \text{if } P = (12)(3), \\ (0, 0, b) & \text{if } P = (13)(2), \\ \text{Conv}\{(0, c-b, b), (0, a, c-a)\} & \text{if } P = (1)(23), \\ (0, d/2 - (b-a)/2, d/2 + (b-a)/2) & \text{if } P = (123) \end{cases}$$

Clearly $(1)(23) \text{ dom}(M_1^{(i)}) (12)(3)$ and $(1)(23) \text{ dom}(M_1^{(i)}) (13)(2)$.

Also since $(0, c/2 - (b-a)/2, c/2 + (b-a)/2) \in M_1^{(i)}((1)(23))$ and

$c > d$, $(1)(23) \text{ dom}(M_1^{(i)}) (123)$. The transition graph is shown in

Figure 8.1. Hence Case (i) follows.

(ii) In this case, the bargaining set is as in (8.3) except for c.s. (123) which is

$$M_1^{(i)}((123)) = M_1^{(i)}((1)(23)).$$

Therefore (ii) follows. (See Figure 8.2.)

(iii) Case 1) $c > a+b$

Here the bargaining set is as in (8.3) except for c.s. (123) which is given by

$$M_1^{(i)}((123)) = \{(x_1, x_2, x_3) : x_1 + x_2 \geq a, x_1 + x_3 \geq b, x_2 + x_3 \geq c, \text{ and } x_1 + x_2 + x_3 = d\}.$$

For each $(0, x_2, c-x_2) \in M_1^{(i)}((1)(23))$ where $a \leq x_2 \leq c-b$, we have $((d-c)/3, x_2 + (d-c)/3, c-x_2 + (d-c)/3) \in M_1^{(i)}((123))$. Hence $(123) \text{ dom}(M_1^{(i)}) (1)(23)$. The transition digraph is shown in Figure 8.3.

(iii) Case 2) $c \leq a+b$

In this case the bargaining set is given by

$$(8.4) \quad M_1^{(i)}(P) = \begin{cases} (0, 0, 0) & \text{if } P = (1)(2)(3), \\ (p_1, p_2, 0) & \text{if } P = (12)(3), \\ (p_1, 0, p_3) & \text{if } P = (13)(2), \\ (0, p_2, p_3) & \text{if } P = (1)(23), \\ \text{Co}((123)) & \text{if } P = (123). \end{cases}$$

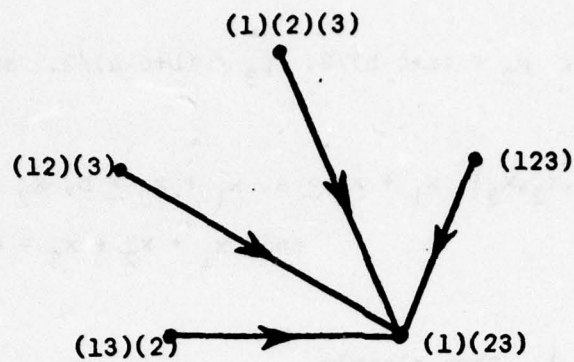


Figure 8.1. The transition digraph in Theorem 8.2, (i).

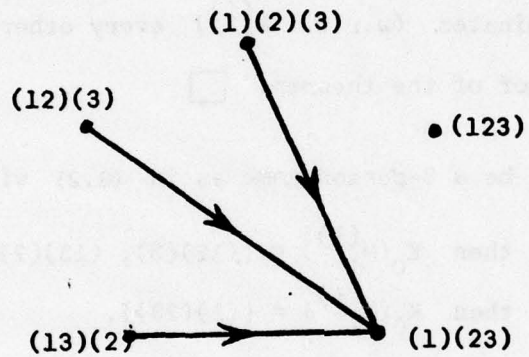


Figure 8.2. The transition digraph in Theorem 8.2, (ii).

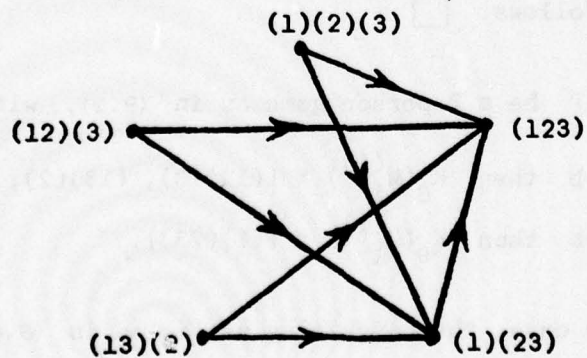


Figure 8.3. The transition digraph in Theorem 8.2, (iii) case 1).

where $p_1 = (a+b-c)/2$, $p_2 = (a+c-b)/2$, $p_3 = (b+c-a)/2$, and

$$\text{Co}((123)) = \{(x_1, x_2, x_3): x_1 + x_2 \geq a, x_1 + x_3 \geq b, x_2 + x_3 \geq c, \\ \text{and } x_1 + x_2 + x_3 = d\}.$$

Let $p = (p_1 + p_2 + p_3)$, then clearly,

$$(p_1 + (d-p)/3, p_2 + (d-p)/3, p_3 + (d-p)/3) \in M_1^{(i)}((123))$$

Hence c.s. (123) dominates (w.r.t. $M_1^{(i)}$) every other c.s. This case completes the proof of the theorem. \square

Theorem 8.3. Let Γ be a 3-person game as in (8.2) with $d = (a+b+c)/2$.

- (i) If $c \leq a+b$ then $K_0(M_1^{(i)}) = \{(12)(3), (13)(2), (1)(23), (123)\}$.
- (ii) If $c > a+b$ then $K_0(M_1^{(i)}) = \{(1)(23)\}$.

Proof: (i) In this case, the bargaining set is as in (8.4) with $M_1^{(i)}((123)) = (p_1, p_2, p_3)$. The result clearly follows.

(ii) In this case, the bargaining set is as in (8.3). Since $d < c$, the result follows. \square

Theorem 8.4. Let Γ be a 3-person game as in (8.2), with $d < (a+b+c)/2$.

- (i) If $c \leq a+b$ then $K_0(M_1^{(i)}) = \{(12)(3), (13)(2), (1)(23)\}$.
- (ii) If $c > a+b$ then $K_0(M_1^{(i)}) = \{(1)(23)\}$.

Proof: (i) In this case, the bargaining set is as in (8.4) except for c.s. (123) for which it is given by

$$(8.5) \quad M_1^{(i)}((123)) = \begin{cases} (p_1 + (d-p)/3, p_2 + (d-p)/3, p_3 + (d-p)/3) & \text{if } 2c-a-b \leq d \\ (0, d/2 - (b-a)/2, d/2 + (b-a)/2) & \text{if } b-a \leq d < 2c-a-b \\ (0, 0, d) & \text{if } d < b-a. \end{cases}$$

In all cases, the transition graph is presented in Figure 8.4. Therefore (i) follows.

(ii) In this case the bargaining set is as in (8.3) except for c.s. (123) for which the bargaining set is as in (8.5). The transition graph is shown in Figure 8.5. Hence the result follows. \square

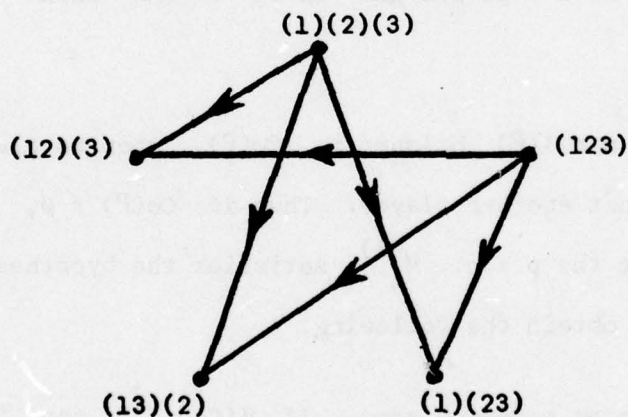


Figure 8.4. The transition graph in Theorem 8.4, (i).

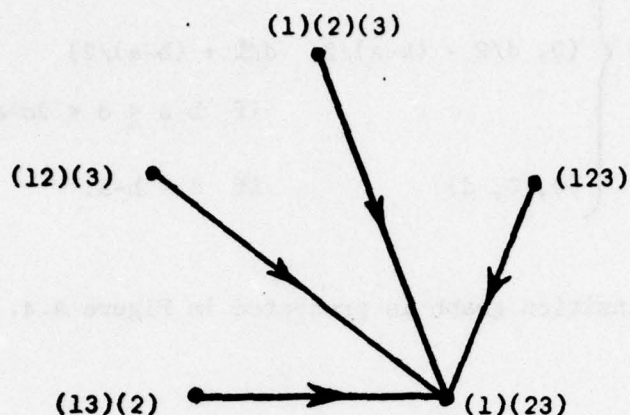


Figure 8.5. The transition graph in Theorem 8.4 (ii).

Since Theorems 8.2, 8.3 and 8.4 cover all cases, we have proved the following.

Theorem 8.5. Let Γ be a 3-person game as in (8.2). Then $K_0(M_1^{(i)}) \neq \emptyset$.

For every $P \in \Pi$, if $x \in I(P)$ belongs to $\text{Co}(P)$, then no player can have an objection against another player. Thus if $\text{Co}(P) \neq \emptyset$, $\text{Co}(P) \subset M_1^{(i)}(P)$. Hence the p.s.c. $M_1^{(i)}$ satisfies the hypothesis of Corollary 6.2. So we obtain the following.

Lemma 8.6. Let Γ be an n -person game. If $\Pi(\text{Co}) \neq \emptyset$ then $K_0(M_1^{(i)}) \neq \emptyset$. In fact $K_0(M_1^{(i)}) \supset \Pi_Z$.

Proof: This is a consequence of Corollary 6.2 and Theorem 6.3. \square

No general existence theorem for $K_0(M_1^{(i)})$ is known at this time.

Example 8.1 illustrates a pathology for $K_0(M_1^{(i)})$ which is due to

a "flaw" in the properties of the bargaining set.

Example 8.1. Let Γ be a 5-person game with

$$v(12) = 10, \quad v(35) = 85, \quad v(134) = 148, \quad v(2345) = 160, \quad \text{and} \\ v(R) = 0 \quad \text{for all other } R \subset N.$$

A simple computation reveals that the bargaining set is given by

$$M_1^{(i)}(P) = \begin{cases} (0, 10, 0, 0, 0) & \text{if } P = (12)(3)(4)(5), (12)(3)(45), \\ & (12)(345) \text{ or } (12)(34)(5), \\ (0, 0, 85, 0, 0) & \text{if } P = (1)(2)(35)(4), (14)(35)(2), \\ & (124)(35) \text{ or } (1)(24)(35), \\ (0, 0, 148, 0, 0) & \text{if } P = (134)(2)(5) \text{ or } (134)(25), \\ (0, 10 \leq x_2 \leq 12, 160-x_2, 0, 0)^\dagger & \text{if } P = (1)(2345), \\ (0, 10, 85, 0, 0) & \text{if } P = (12)(35)(4), \\ (0, 0, 0, 0, 0) & \text{for all other } P \in \Pi. \end{cases}$$

Note that in every c.s. that contains a coalition which has a positive value, at least one player in the coalition gets zero payoff in the bargaining set. As a result, due to Condition (3.5) in the definition of domination, no c.s. dominates another c.s. Hence $K_0(M_1^{(i)}) = \Pi$.

The above example exhibits a flaw in the properties of the bargaining set. E.g., in the c.s. $(12)(35)(4)$ player 5 gets zero payoff in the

[†]Denotes the set $\{(0, x_2, 160-x_2, 0, 0): 10 \leq x_2 \leq 12\}$.

bargaining set. This is because player 5 has no 'bargaining power' at all vis-à-vis player 3. Since there are no coalitions with a positive value that contains player 5 but not player 3, player 5 cannot even object! However the payoff in the bargaining is counter-intuitive because we could argue: Why should player 5 enter into a coalition with player 3 if his share of the resulting coalitional value is the same as what the player could have obtained had he been in a coalition by himself? In this respect, we could say that the bargaining set is derived entirely from the bargaining positions of the players in the process of coalition formation in contrast with the Shapley value which is derived entirely from the characteristic function of the game. These two p.s.c.'s reflect two extreme view points in looking at solutions of cooperative games in characteristic function form. A major research problem is to define a p.s.c. that exhibits both the strategic value and the bargaining power of the players.

One method of attacking this problem in the case of the bargaining set is to regard the bargaining set as an idealization (of the bargaining process) and relax the definition of an objection by ϵ , where ϵ is a small positive real number. More formally, let $x \in I(P)$ and i and j be two distinct players in a coalition $P_k \in P$. An ϵ -objection of i against j is a vector y^R , where R is a coalition containing player i but not j , whose coordinates y_l satisfy $y_i > x_i + \epsilon$, $y_l \geq x_l$ for all $l \in R$, and $\sum_{l \in R} y_l = v(R)$. A counter-objection to this ϵ -objection is defined as before. We say $x \in I(P)$ is ϵ -stable if for each ϵ -objection in x , there is a counter-objection. The ϵ -bargaining set, denoted by $M_{1,\epsilon}^{(i)}$, corresponding to c.s. $P \in \Pi$ is the set of all ϵ -stable $x \in I(P)$, i.e.,

$$(8.6) \quad M_{1,\epsilon}^{(i)}(P) = \{x \in I(P) : x \text{ is } \epsilon\text{-stable}\}.$$

We could regard ϵ as a 'sacrifice' each player is willing to make (if necessary) for coalitional stability.

Note that the results in Theorems 8.2, 8.3, 8.4 and 8.5 as well as Lemma 8.6 remain unchanged if we replace $M_1^{(i)}$ by $M_{1,\epsilon}^{(i)}$.

Example 8.2. Consider the game in Example 8.1. The ϵ -bargaining set is given by

$$M_{1,\epsilon}^{(i)}(P) = \begin{cases} (0 \leq x_1 \leq \epsilon, 10-x_1, 0, 0, 0) & \text{if } P = (12)(3)(4)(5), \\ & (12)(3)(45), (12)(345) \text{ or } (12)(34)(5), \\ (0, 0, 85-x_5, 0, 0 \leq x_5 \leq \epsilon) & \text{if } P = (1)(2)(35)(4), \\ & (14)(2)(35), (124)(35) \text{ or } (1)(24)(35), \\ (0 \leq x_1 \leq \epsilon, 10-x_1, 85-x_5, 0, 0 \leq x_5 \leq \epsilon) & \text{if } P = (12)(35)(4), \\ (0 \leq x_1 < \epsilon, 0, 148-x_1-x_4, 0 \leq x_4 \leq \epsilon, 0) & \text{if } P = (134)(25) \text{ or} \\ & (134)(2)(5), \\ (0, 10-\epsilon \leq x_2 \leq 12+\epsilon, 160-x_2-x_4-x_5, 0 \leq x_4 \leq \epsilon, 0 \leq x_5 \leq \epsilon) & \\ & \text{if } P = (1)(2345), \\ (0, 0, 0, 0, 0) & \text{for all other } P \in \Pi. \end{cases}$$

It is clear that $K_0(M_{1,\epsilon}^{(i)}) = \{(12)(35)(4), (134)(2)(5), (134)(25), (1)(2345)\}$ which is more intuitive than $K_0(M_1^{(i)}) = \Pi$.

Example 8.3. (The Chemical Company Game. See Anderson and Traynor [1].)

Two chemical companies C_1 and C_2 supply two fabricating companies

F_1 and F_2 . The permissible coalition structures are:

$$\begin{aligned} P_1 &= (C_1)(C_2)(F_1)(F_2), & P_2 &= (C_1F_1)(C_2)(F_2), \\ P_3 &= (C_1F_2)(C_2)(F_1), & P_4 &= (C_1)(C_2F_1)(F_2), \\ P_5 &= (C_1)(C_2F_1)(F_1), & P_6 &= (C_1F_1)(C_2F_2), \\ P_7 &= (C_1F_2)(C_2F_1). \end{aligned}$$

The respective payoffs (profits) to these coalitions in the particular coalition structures are:

$$\begin{aligned} P_1: & 25, 15, 75, 100. & P_2: & 300, 25, 110. \\ P_3: & 500, 30, 85. & P_4: & 28, 200, 105. \\ P_5: & 30, 425, 90. & P_6: & 400, 600. \\ P_7: & 700, 300. \end{aligned}$$

This "partition function" induces the characteristic function:

$$\begin{aligned} v(C_1) &= 25, & v(C_2) &= 15, & v(F_1) &= 75, & v(F_2) &= 100, & v(C_1, F_1) &= 300, \\ v(C_1, F_2) &= 500, & v(C_2, F_1) &= 200, & v(C_2, F_2) &= 425. \end{aligned}$$

The bargaining set $M_1^{(i)}$ is given by

$$M_1^{(i)}(P) = \begin{cases} (25, 15, 75, 100) & \text{if } P = P_1 \\ (115 \leq x_1 \leq 225, 15, 300-x_1, 100) & \text{if } P = P_2 \\ (90 \leq x_1 \leq 225, 15, 75, 500-x_1) & \text{if } P = P_3 \\ (25, 15 \leq x_2 \leq 125, 200-x_2, 100) & \text{if } P = P_4 \end{cases}$$

$$M_1^{(i)}(P) = \begin{cases} (25, 15 \leq x_2 \leq 125, 75, 425-x_2) & \text{if } P = P_5 \\ (x_1, x_2, 300-x_1, 425-x_2) & \text{if } P = P_6 \\ \text{where } x_1, x_2 \text{ are as in Figure 8.6.} \\ (y_1, y_2, 200-y_2, 500-y_1) & \text{if } P = P_7 \\ \text{where } y_1, y_2 \text{ are as in Figure 8.7.} \end{cases}$$

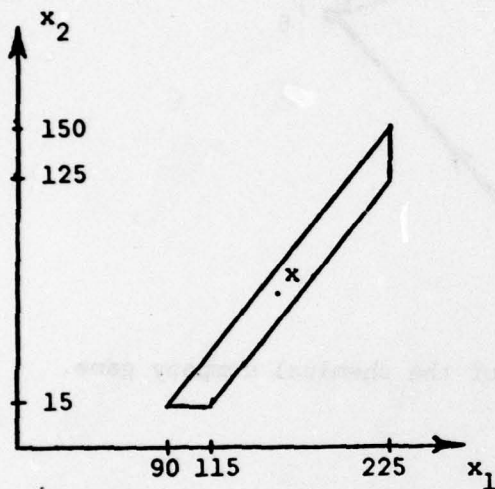


Figure 8.6. The bargaining set $M_1^{(i)}(P_6)$ for the chemical company game.

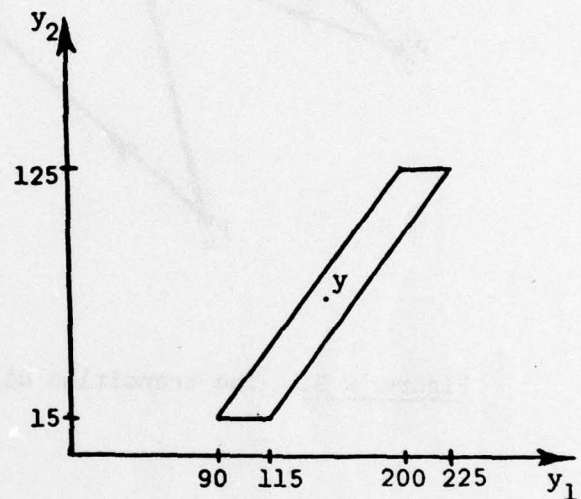


Figure 8.7. The bargaining set $M_1^{(i)}(P_7)$ for the chemical company game.

The transition digraph is shown in Figure 8.8. Hence

$$K_0(M_1^{(i)}) = \{(C_1F_1)(C_2F_2), (C_1F_2)(C_2F_1)\}.$$

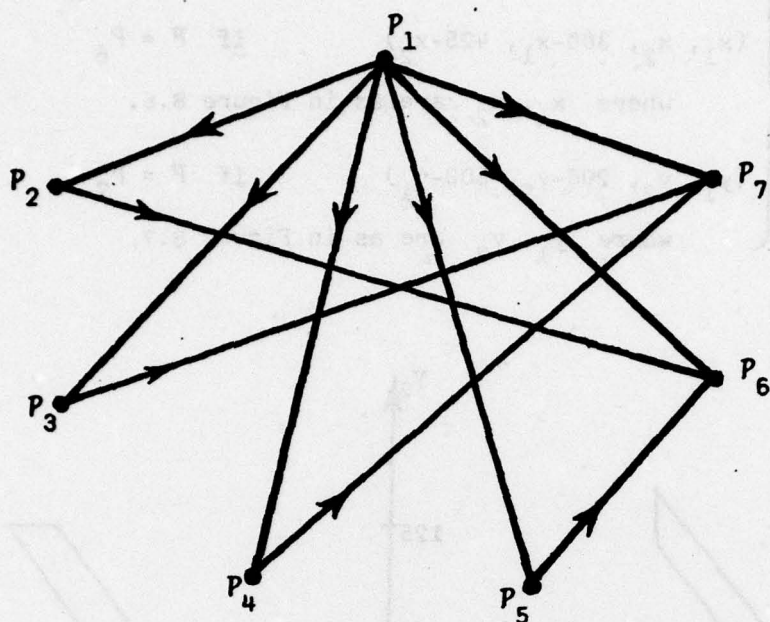


Figure 8.8. The transition digraph of the chemical company game.

9. Some Modifications of the Coalition Structure Model

In this section, we look at some modifications of the domination relation in the abstract game $(\Pi(S), \text{dom}(S))$. We define two other domination relations one of which is stronger than $\text{dom}(S)$ and the other weaker than $\text{dom}(S)$.

Definition 9.1. Let $P_1, P_2 \in \Pi(S)$ and S be a p.s.c. Then P_1 weakly dominates P_2 , denoted by $P_1 \text{ w-dom}(S) P_2$, iff

- (9.1) for each $y \in S(P_2)$, \exists a nonempty $R \in P_1$ and $x \in S(P_1)$ such that $x_i > y_i$ for all $i \in R$.

Definition 9.2. Let $P_1, P_2 \in \Pi(S)$ and S be a p.s.c. Then P_1 strongly dominates P_2 , denoted by $P_1 \text{ s-dom}(S) P_2$, iff \exists a nonempty $R \in P_1$ and $x \in S(P_1)$ such that for all $y \in S(P_2)$, $x_i > y_i$ for all $i \in R$.

The following relations are direct consequences of Definitions 3.6, 9.1 and 9.2.

(9.2) If $P_1 \text{ s-dom}(S) P_2$, then $P_1 \text{ dom}(S) P_2$.

(9.3) If $P_1 \text{ dom}(S) P_2$, then $P_1 \text{ w-dom}(S) P_2$.

Let $K_{0,w}(S)$ and $K_{0,s}(S)$ denote the cores of the abstract games $(\Pi(S), \text{w-dom}(S))$ and $(\Pi(S), \text{s-dom}(S))$ respectively. As a consequence of Relations (9.2) and (9.3), we have

(9.4) $K_{0,s}(S) \supset K_0(S) \supset K_{0,w}(S).$

Also, if S is a p.s.c. such that for each $P \in \Pi$, $S(P)$ is either a single point set in E^n or an empty set, then

(9.5) $K_{0,s}(S) = K_0(S) = K_{0,w}(S).$

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APPENDIX

The Aumann-Dreze Generalization of the Shapley Value for all Simple Games with Four or Fewer Players

The table on the following pages contains all distinct proper simple games of four or fewer players excluding dummies. All winning coalitions are listed--the minimal winning coalitions are listed first and separated from the rest by a semicolon. The weighted voting representation given in column 4 are the simplest ones. The Shapley value ϕ of a c.s. depends only on the winning coalition contained in the c.s. The Shapley value of all c.s.'s containing winning coalitions, in the sequence as in column 3, is given in column 5. The Shapley value of a c.s. not containing any winning coalition is zero for each player and therefore is not given in column 5. Column 6 contains all c.s.'s in $K_0(\phi)$ identified by the winning coalition it contains. The last column indicates whether the game exhibits the paradox of smaller coalitions or not.

Number of Players	W	Weighted Voting Representation	ϕ	$K_0(\phi)$	Paradox?
1	A	[1; 1]	(1)	A	no
2	AB	[2; 1, 1]	(1/2, 1/2)	AB	no
3	ABC	[3; 1, 1, 1]	(1/3, 1/3, 1/3)	ABC	no
3	AB, AC, ABC	[3; 2, 1, 1]	(1/2, 1/2, 0), (1/2, 0, 1/2), (2/3, 1/6, 1/6)	AB, AC, ABC	yes
3	AB, AC, BC, ABC	[2; 1, 1, 1]	(1/2, 1/2, 0), (1/2, 0, 1/2), (0, 1/2, 1/2), (1/3, 1/3, 1/3)	AB, AC, BC	no
4	ABCD	[4; 1, 1, 1, 1]	(1/4, 1/4, 1/4, 1/4)	ABCD	no
4	ABC, ABD, ABCD	[5; 2, 2, 1, 1]	(1/3, 1/3, 1/3, 0), (1/3, 1/3, 0, 1/3), (5/12, 5/12, 1/12, 1/12)	ABC, ABD, ABCD	yes
4	ABC, ABD, ACD, ABCD	[4; 2, 1, 1, 1]	(1/3, 1/3, 1/3, 0), (1/3, 1/3, 0, 1/3), (1/3, 0, 1/3, 1/3), (1/2, 1/6, 1/6, 1/6)	ABC, ABD, ACD, ABCD	yes
4	ABC, ABD, ACD, BCD, ABCD	[3; 1, 1, 1, 1]	(1/3, 1/3, 1/3, 0), (1/3, 1/3, 0, 1/3), (1/3, 0, 1/3, 1/3), (0, 1/3, 1/3, 1/3), (1/4, 1/4, 1/4, 1/4)	ABC, ABD, ACD, BCD	no
4	AB, ACD, ABD, ABC, ABCD	[5; 3, 2, 1, 1]	(1/2, 1/2, 0, 0), (1/3, 0, 1/3, 1/3), (1/2, 1/2, 0, 0), (7/12, 3/12, 1/12, 1/12)	AB, ABD, ABC, ABCD	yes
4	AB, ACD, BCD, ABD, ABC, ABCD	[4; 2, 2, 1, 1]	(1/2, 1/2, 0, 0), (1/3, 0, 1/3, 1/3), (1, 1/3, 1/3, 1/3), (1/2, 1/2, 0, 0), (1/2, 1/2, 0, 0), (1/3, 1/3, 1/6, 1/6)	AB, ABD, ABC, ABCD	no

Table A.1. The Aumann-Dreze generalization of the Shapley value for simple games.

Number of Players	W	Weighted Majority Representation	ϕ	$K_0(\phi)$	Paradox?
4	AB, AC, BCD; ACD, ABD, ABC, ABCD	[5; 3, 2, 2, 1]	(1/2, 1/2, 0, 0), (1/2, 0, 1/2, 0), (0, 1/3, 1/3, 1/3), (1/2, 0, 1/2, 0), (1/2, 1/2, 0, 0), (2/3, 1/6, 0, 0), (5/12, 3/12, 3/12, 1/12)	AB, ABD, ABC	yes
4	AB, AC, AD; ABC, ABD, ACD, ABCD	[4; 3, 1, 1, 1]	(1/2, 1/2, 0, 0), (1/2, 0, 1/2, 0), (1/2, 0, 0, 1/2), (2/3, 1/6, 0, 0), (2/3, 1/6, 0, 1/6), (9/12, 1/12, 1/12, 1/12)	ABC, ABD, ACD, ABCD	yes
4	AB, AC, AD, BCD; ABC, ABD, ACD, ABCD	[3; 2, 1, 1, 1]	(1/2, 1/2, 0, 0), (1/2, 0, 1/2, 0), (1/2, 0, 0, 1/2), (0, 1/3, 1/3, 1/3), (2/3, 1/6, 1/6, 0), (2/3, 1/6, 0, 1/6), (2/3, 0, 1/6, 1/6), (1/2, 1/6, 1/6, 1/6)	\emptyset	yes

Table A.1. (continued)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This paper deals with the question of coalition formation in n-person cooperative games. Two abstract game models of coalition formation are proposed. We then study the core and the dynamic solution of these abstract games. These models assume that there is a rule governing the allocation of payoffs to each player in each coalition structure called a payoff solution concept. The predictions of these models are characterized for the special case of games with side payments using various payoff solution concepts such as the individually rational payoffs, the core, the Shapley value and the bargaining set ^(M) . Some modifications of these models are also discussed.		